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Convergence of tectonic reconstructions and mantle convection models for significant fluctuations in seafloor spreading

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Abstract

For 50 years of data collection and kinematic reconstruction efforts plate models have provided alternative scenarios for plate motions and seafloor spreading for the past 200 My. However, these efforts are naturally limited by the incomplete preservation of very old seafloor, and therefore the time-dependence of the production of new seafloor is controversial. There is no consensus on how much it has varied in the past 200 My, and how it could have fluctuated over longer timescales. We explore how seafloor spreading and continental drift evolve over long geological periods using independently derived models: a recently developed geodynamic modelling approach and state-of-the-art plate reconstructions. Both kinematic reconstructions and geodynamic models converge on variations by a factor of 2 in the rate of production of new seafloor over a Wilson cycle, with concomitant changes

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of the shape of the area-age distribution of the seafloor between end members of rectangular, triangular and skewed distributions. Convection models show that significant fluctuations over longer periods (~1 Gy) should exist, involving changes in ridge length and global tectonic reorganisations. Although independent, both convection models and kinematic reconstructions suggest that changes in ridge length are at least as significant as spreading rate fluctuations in driving changes in the seafloor area-age distribution through time.

Keywords: Mantle convection, Plate tectonics, Reconstruction, Seafloor spreading

1. Introduction

The theory of plate tectonics has provided the necessary framework for reconstructing ocean basins, including now subducted seafloor, and paleogeography (Kominz, 1984). Over 50 years of data collection and kinematic reconstruction efforts have led to significant improvements in plate tectonic modelling (Pilger, 1982; Rowley and Lottes, 1988; Scotese et al., 1988; Lithgow-Bertelloni and Richards, 1998; Müller et al., 1997; Seton et al., 2012). Plate tectonic models describing seafloor area-age distributions with relatively small uncertainties exist only for times where geological and geophysical data coverage is sufficient. Challenges remain for reconstructing ancient ocean basins and associated plate boundaries for times earlier than 200 Ma, as they are naturally limited by the preservation of very old seafloor. In addition, only 5% of the history of the planet can be reconstructed using evidence from geological and geophysical data.

However, geodynamic models can now help to evaluate how seafloor spreading evolves over longer time periods. Recent numerical models of mantle convection with pseudo-plasticity can generate long-term solutions producing a form of seafloor spreading (Moresi and Solomatov, 1998; Trompert and Hansen, 1998; Tackley, 2000), although developing a more complete and consistent physical model for the rheology will eventually be required (Bercovici, 2003; Bercovici and Ricard, 2012). These models have a mechanically strong boundary layer at the surface, which becomes weak in regions of higher stresses. Hence, strain localises in relatively narrow regions while rigid body motion dominates elsewhere (van Heck and Tackley, 2008). These models also generate a significant toroidal component in the surface velocity field, as observed on Earth. The introduction of models of continental lithosphere (Yoshida, 2010; Rolf and Tackley, 2011) further improve the quality of such predictions: the computed distribution of seafloor ages reproduces the consumption of young seafloor as observed on the present-day Earth (Coltice et al., 2012).

The time-dependence of the production of new seafloor has long been debated and there is no consensus on how much it has varied in the past 150 My, and how it could have fluctuated over longer timescales. Using plate reconstructions, Parsons (1982) and Rowley (2002) proposed that the area-age distribution of the seafloor has experienced limited fluctuations in the past 200 My, while others have suggested that larger variations would fit the observations equally well (Demicco, 2004; Seton et al., 2009). In addition, relatively fast seafloor spreading was proposed for the mid-Cenozoic

(Conrad and Lithgow-Bertelloni, 2007). A careful analysis by Becker et al. (2009) concluded that the present-day area vs. age distribution of the seafloor accounts for significant fluctuations of the rate of seafloor production in the past 200 My, an interpretation opposite to that reached by Parsons (1982) and Rowley (2002).

Here we investigate the global dynamics of seafloor spreading using two independent modelling approaches: state-of-the-art plate reconstructions and geodynamic models. Both kinematic reconstructions and geodynamic models converge to suggest that the rate of production of new seafloor can vary by a factor of 2 over a Wilson cycle, with concomitant changes of the shape of the area-age distribution of the seafloor.

2. The area-age distribution of the seafloor

The evolution of the area-age distribution of the seafloor through time is of fundamental importance since it impacts on global variations in heat flow, tectonic forces and sea-level. The area-age distribution provides a statistical representation of the state of the seafloor. It can be used to quantitatively compare seafloor spreading states with different continental configurations and plate distributions.

The evolution of the area-age distribution has been the subject of intense debate in the past 30 years. The present-day distribution displays a linear decrease of the area for increasing age. Young seafloor dominates, but areas with ages as old as 180 Ma exist. The shape of this distribution is called triangular. The physics behind this distribution has been questioned by Labrosse and Jaupart (2007), particularly because it suggests that lithosphere of young age (hot) is subducted with the same probability as that of older ages (cold). Indeed, a principle of convection is that when a material at the surface of a thermal boundary layer of convecting fluid has cooled sufficiently its buoyancy becomes large enough to start sinking into the viscous interior. The onset of the downwellings corresponds to a critical value of the local Rayleigh number, which in dimensional values can be converted to a critical age. As a consequence, convection appears to favour the sinking of lithosphere only when a critical age is attained, implying that a rectangular distribution is expected.

Two effects can be proposed to force a convective system to adopt a distribution that is skewed (or triangular): continent configuration and time-dependence of the flow. Continents are relatively unsinkable and conductive, therefore the entire continental area cannot participate in seafloor spreading and subduction. As observed on Earth today, subduction zones tend to locate themselves at the continent-ocean boundary. As shown in Figure 1, the orientation and shape of the subduction zone along a continent, relative to the opening ridge governs the shape of the area-age distribution.

The time-dependence of seafloor spreading also implies modifications of the area-age distribution, as proposed earlier by Demicco (2004). Indeed, since the integral of the distribution is the total seafloor area, a conserved quantity in recent geological time, increasing the rate of production of new seafloor necessarily involves the sinking of older seafloor. As shown in Figure 2, fluctuations of seafloor production can lead to triangular-like shape. The more time-dependent the system is, the more variable the area-age distribution can be. However, the time-dependence of the rate of production of new seafloor has been challenged by Parsons (1982) and Rowley (2002), who propose that the fluctuations in the past 150 My do not exceed 30% of the present-day value. In the following we will address the extent of the time-dependence with the most recent plate reconstructions and mantle convection models.

3. Reconstructed seafloor history since 200 Ma

We reconstruct the seafloor spreading history for the past 200 million years based on a merged absolute reference frame (O'Neill et al. (2005) and Steinberger and Torsvik (2009)) with relative plate motions based on Seton et al. (2012). The plate reconstructions are underpinned by over 70,000 magnetic anomaly and fracture zone identifications for currently preserved crust. For crust that has been subducted, we use simple assumptions of spreading symmetry, adherence to the rules of plate tectonics and onshore geological data to constrain our plate reconstructions (Müller et al., 2008; Seton et al., 2012). We extend the model back to the Triassic (250 Ma) by incorporating a longer history of seafloor spreading between the three major plates that form Panthalassa (Izanagi, Farallon, Phoenix plates) similar to its Jurassic-Cretaceous opening history, the closure of the Mongol-Okhotsk Ocean based on Van der Voo et al. (1999) and a more extensive paleo-Tethys ocean largely consistent with Stampfli and Borel (2002) and Golonka (2007). Our plate reconstructions also include an accompanying set of continuously closed plate polygons (CPP) and plate boundaries (Gurnis et al., 2012) allowing us to track the properties of the plates themselves through time.

In the Triassic, the vast Panthalassic and the smaller Tethys Ocean surrounded the supercontinent, Pangaea. Panthalassa, modeled as a simple three plate spreading system between the Izanagi, Farallon and Phoenix plates dominated the planet, accounting for over half iof ts surface area. The expansion of the Tethys Ocean at the expense of the palaeo-Tethys (which was being consumed along the Tethyan subduction zone) was accommodated by the Meso-Tethys spreading ridge system. The predominant plate boundary regime operating in the Triassic/Jurassic was subduction, particularly around the rim of Panthalassa and along the northern Tethyan margin.

By 200 Ma, Pangaea was undergoing slow continental break-up centered along a rift zone extending along the north and central Atlantic, through eastern Africa and southern South America (Figure 3) leading to the onset of a progressive increase in ridge lengths and increasing crustal production (Figure 4). The initial break-up separated Pangaea into Laurentia, Laurasia and the China/Amuria block in the northern hemisphere and Gondwanaland in the southern hemisphere. The birth of the Pacific plate within Panthalassa at 190 Ma and the change from rift to drift along the central Atlantic initiated a period of younging of the ocean floor and increase in the global ridge length. The final break-up of Pangaea was established by 160 Ma, dividing Gondwanaland into its eastern and western portions via rifting and seafloor spreading between Africa, India, Antarctica, Madagascar and east Gondwana. The closure of the palaeo-Tethys, composed of mature oceanic crust was completed by around 170 Ma and the Mongol-Okhotsk Ocean by 150 Ma. The continual growth of the Pacific plate at the expense of the Izanagi, Farallon and Phoenix plates led to an increasing length of mid ocean ridges and production of young ocean crust in the Pacific domain (Figure 3). The higher proportion of new crust produced at the mid ocean ridges compared to old crust being destroyed along the subduction zones of the northern Tethys and circum-Panthalassa is reflected in the change from a rectangular-like area-age distribution during Pangaea amalgamation towards a triangular distribution, reflecting a scenario consistent with a near constant production of oceanic lithosphere compared to what is destroyed, similar to the present-day state of the planet (Figure 3).

The early-mid Cretaceous marks a significant increase in seafloor spreading rates in Panthalassa, as documented by magnetic lineations in the Pacific Ocean (Larson and Chase, 1972; Nakanishi and Winterer, 1992; Seton et al., 2009). Seafloor spreading occurred in a complex arrangement between the Pacific, Farallon, Izanagi and Phoenix plates. At 120 Ma, spreading was further complicated by the break-up of the Ontong-Java-Manihiki-Hikurangi plateaus (Taylor, 2006; Chandler et al., 2012), leading to a marked increase in the length of the mid ocean ridge system until its termination at $\sim$85 Ma. During this time period, the majority of old ocean floor on the edges of Panthalassa was subducted, leaving behind a significantly younger Panthalassic ocean per unit area and the highest rates of crustal production observed from Mesozoic to the present day (Figure 4). The mid Cretaceous also corresponds to the peak time for African intra-continental rifts, associated with the opening of the South and Equatorial Atlantic. While the mid ocean ridges of the Meso-Tethys were progressively being subducted along the southern Eurasian margin, the spreading systems of the proto-Indian Ocean such as the west Australian margins, the Enderby Basin and along east Africa were producing new crust. The mid Cretaceous (120-80 Ma) is characterized by a minimum of the average age of oceanic lithosphere (∼38 My old), mid ocean ridge lengths (>60,000 km), crustal production rates (> 5.5 km y^{-1}) (Figure 4) and a substantial decrease in the proportion of older ocean floor being subducted. This is shown in the skewness of the area-age distribution reflecting a high proportion of young ocean floor at this time compared to older ocean floor.

Since the peak of crustal production and seafloor spreading rates in the mid Cretaceous, there has been a progressive decline in seafloor spreading rates (Seton et al., 2009), crustal production (Figure 4) and a steady increase in the area-age distribution of the oceanic lithosphere. Although the decline in crustal production initiated at around 80 Ma, there is a major inflection point in mid ocean ridge lengths and age of the oceanic lithosphere at 60-50 Ma, related to the destruction of the margin-wide Pacific-Izanagi ridge system and consumption of remnants of the Izanagi plate. This major event marked the change over from a skewed distribution towards a triangular distribution indicating the more constant crustal production that we observe today.

Over the last 250 My, our reconstructions predict that the seafloor production rate changes quite significantly, by a factor of 2 to 3, contrary to previous studies based on present day preserved ocean crust (Parsons, 1982; Rowley, 2002). We find that the rates of crustal production and the area-age distributions can be related to cycles of supercontinent amalgamation and break-up. Supercontinent amalgamation is related to a rectangular-like distribution and low/moderate crustal production rates whereas break-up is associated with a triangular distribution, which eventually develops into a skewed distribution towards the young end as progressively new crust is created at the expense of older crust.

4. Convection models with seafloor spreading and continental drift

-Mantle convection with self-consistent plate generation is an independent and complementary approach to plate tectonic reconstructions for the investigation of the fluctuations of seafloor spreading. Convection models with self-consistent plate generation provide an analog of Earth's mantle convection which, contrary to the plate reconstructions of tectonic history that are limited in time, allows for the investigation of how seafloor spreading may have functioned over longer geological time. However, convection models themselves cannot compute a solution directly comparable to the Earth because, for instance, initial conditions are unknown. The numerical models employed in this study are the first generation of 3D spherical mantle convection models that self-consistently generate a form a seafloor spreading and continental drift. They are built on successive generations of software that started with the cartesian models of Tackley (2000) incorporating pseudo-plasticity, were extended to spherical geometry (van Heck and Tackley, 2008) and now include a basic model of continental lithosphere (Yoshida, 2010; Rolf and Tackley, 2011), represented as thick, buoyant and 100 times more viscous rafts. The numerical models used here are described in more detail in Rolf and Tackley (2011) and Rolf et al. (2012). The resolution here is improved relative to our previous publications, reaching as little as 30 km vertically in the top boundary layer. This resolution appears relatively crude, but is sufficient to resolve the physical processes studied here (when made possible, observed differences with regards to results of Coltice et al. (2012) using lower resolution are small) and is limited by the fact that computing a 3D time-dependent spherical mantle convection solution with 7 orders of magnitude variation in viscosity is already very demanding.

Tackley (2000) developed diagnostics to evaluate how the computed solutions reproduce characteristics of Earth's plate dynamics: the plateness, which evaluates how close surface motion is to that of rigid plates deforming only at their boundaries, mobility, which evaluates whether surface plates are moving with a similar velocity to underlying mantle flow, and the toroidal to poloidal ratio, which evaluates the role of transform motion. The computed solutions presented here display a high degree of plateness, mobility and toroidal to poloidal ratio, similar to those presented in van Heck and Tackley (2008). They generate area-age distributions which are often triangular, as that of the present-day Earth (Coltice et al., 2012), suggesting a form of seafloor spreading comparable to observations. The continental rafts drift apart in the presented models but breakup is slower than observed on Earth (supercontinents can persist for 500-1000 My). The description of the continental lithosphere (which on Earth has weaker and thinner parts) and of the rheology, which could include a memory component, would potentially improve this aspect, especially for more effective dispersal. Such models are currently in development.

The models presented here are at statistical steady-state. Heating is internal except in one case with 14% basal heating. Three values of the non-dimensional yield stress (the maximum stress material can sustain, before deforming plastically) are used here: 5×10^3 (low), 10^4 (intermediate) and 1.5×10^4 (high), ensuring a plate-like regime for surface motions with and without continental rafts (Rolf and Tackley, 2011). Higher yield stresses would lead to surface tectonics that is absent (stagnant lid regime) or episodic, i.e. displaying times without any production or consumption of new seafloor interrupted by short events of very high production and consumption. Such a regime is not investigated here since it is does not represent the modern Earth. Cases without continents, with a supercontinent, and with 6 identical continents are considered. The total continental area is kept at 30% of the surface area of the spherical domain. The Rayleigh number (based on the temperature drop over the surface boundary layer) is, 10^6, 10 to 100 times lower than expected on Earth, for computational reasons. As a consequence, timescales are computed with respect to a transit time of 85 My as described in Gurnis and Davies (1986). The calculations are run for at least 3 Gy such that statistics of seafloor production rate and average root-mean square (rms) surface velocity can be made. The seafloor area-age distribution in the models is computed by converting heat flow into an age assuming a half-space cooling model, following the approach of Labrosse and Jaupart (2007) used in Coltice et al. (2012).

5. Synthetic seafloor histories

5.1. An example of seafloor spreading history

Figure 5 shows 746 My of evolution of seafloor spreading and continental drift in a model with 6 continents, intermediate yield stress (10^4) and 14% of core heating. The first 4 model snapshots have been chosen to encompass 200 My and be similar in duration to the reconstruction sequence shown in Figure 3. This sequence is characterised by relatively little continental motion, and thus highlights the effect of seafloor spreading dynamics. The bottom snapshot, taken 549 My later, shows a situation in which the continents have significantly drifted, reflecting a major tectonic reorganisation.

The tectonic evolution in the 200 My sequence displays a situation for which subduction is located mostly around the continents, with 3 main oceanic domains: a western domain with an elongated NE-SW ridge system with a clear triple junction in the North; a median domain with a long N-S ridge system, and an eastern domain with a E-W ridge system. At 746 Ma, the median and eastern domains encircle a continent, ultimately aggregating on the West side to close a section of the N-S ridge system. At 664 Ma, after this closure, the N-S ridge system starts to divide into 2 parts at the equator. The eastern domain starts to be more active, as younger seafloor ages dominate. At 603 Ma, new ridge systems have appeared in the median and eastern domains, the western domain being stable in terms of plate boundaries but production of young seafloor accelerates. A triple junction in the South of the median domain has progressed towards the subduction zone at the edge of a continent. At 549 Ma, the seafloor production rate in the eastern domain decreases and the 2 ridge systems of the median domain have differentiated. Given the area-age distribution, the average age of the seafloor is slightly older than in the previous state. The situation at 0Ma contains continents that have drifted with 3 aggregated continents in the North and 3 aggregated continents in the South. The eastern domain is closing and has almost disappeared. The group of continents that are almost connected at 40^{o}S are here dispersed with a ridge system connecting the median and western domain. An ocean-ocean subduction in the North-West is generated, highlighted by older ages.

This example of a seafloor spreading history computed from a convection model shows significant variations in of the area-age distribution, comparable to those in the plate reconstructions. This is a representative example for the computed models here. At 746 Ma, seafloor spreading is the slowest within Figure 5 and the ridge system is the shortest. The area-age distribution is rectangular-like, with a production rate of new seafloor lower than 3 km^2 y^{-1}. At 603 Ma, where elongation of the ridge system is important, the distribution is skewed and the production rate of new seafloor reaches 5.2 km^2 y^{-1}. Hence, the production rate of new seafloor has doubled over 143 My and the area-age distribution has changed accordingly. The other snapshots show intermediate states, which differ from each other, but display triangular-like area-age distributions like that observed on Earth today.

5.2. Seafloor production evolution

The rate of production of new seafloor is calculated by computing the area that has ages between 0 and 8 My. The maximum seafloor age barely changes in our calculations, being between 200 and 250 My. Because the total area of the seafloor is constant, a change in the rate of production of new seafloor implies a change in the shape of the global distribution, as discussed earlier: older ages have to disappear if new seafloor is generated, and the distribution becomes more skewed. If the rate of production of new seafloor decreases, the distribution becomes more rectangular-like (see Figure 5 at 746 Ma or 549 Ma). Hence the evolution of the rate of production of new seafloor depicted in Figure 6 also expresses the variability of the shape of the distribution.

The average production rate of new seafloor is slightly higher in our numerical solutions than on the present-day Earth. The lowest average production rate is for the case with a supercontinent, at 3.7 km^2 y^{-1}. The highest production rate is for the case with the lower yield stress, i.e. the weaker lithosphere, at 6.3 km^2 y^{-1}. The yield stress is anti-correlated with the average production rate. The stronger the lithosphere, the lower the average production rate of new seafloor.

The fluctuations in the production rate occur in short and intense events in cases with continents and low to intermediate yield stress. The production rate can vary by a factor of 2-3 over 100 My. Such events happen at most once every 1Gy. Without continents and in particular with a higher yield stress, such events barely exist. The case with the strongest lithosphere is least time-dependent, since peak-to-peak fluctuations do not exceed a factor of 2 of the average value. This is reflected by the standard deviation, which is the smallest (15%) for the present calculations; for other cases it is around 20-23%, and and 30% for the supercontinent case. The effects of a small amount of core heating (here: 14%) are small, but higher core heating rates should be explored in the future since recent estimates point to higher values (Pozzo et al., 2012).

The fluctuations in the production rate correlate with the surface velocity. However, peaks in the production rate do not correspond in all cases to peaks in the surface velocity, or at least peaks of the same relative increase. This result confirms the observations made on Figure 5: peaks of production also correspond to increase of ridge length. Hence, the length of ridges varies significantly with time. Methods to quantify precisely the ridge length in such models are under development.

5.3. Timescales of seafloor production fluctuations

To investigate the significance of different periods in the time-series of the rate of production of new seafloor, we have computed periodograms performing Fourier transform, which provide an estimate of the spectral density of the time series of the production of new seafloor. Figure 7 shows that all models display dominant timescales. No convection model presented here features significant periods smaller than 100 My. Most models have major periods around 200 My and 800 My. The supercontinent case and the higher yield stress case both have fluctuations at >1 Gy periods. The case with the strongest lithosphere shows a very long-term period, comparable to the duration of the run. However, because of the truncation of the run length there is certainly a bias for such a long period. Therefore, very long periods with significant power should not be over-interpreted since they suggest periods that >1 Gy are present. Moreover, convection solutions in this study are at statistical steady-state with constant heat sources. Hence, they do not represent seafloor spreading changes caused by the slow cooling of the planet, which becomes significant over a 1 Gy time scale. Interactions between the cooling timescale and the long timescales found here with a constant heat budget are expected. As a consequence, stronger fluctuations over >1 Gy should exist.

Because convection is a self-organising system, it is difficult to interpret timescales. However, the timescale of 200 My could correspond to the instability onset (Howard, 1964), since it corresponds to the maximum age of the seafloor. The longer peak period between 600 and 900 My, could be the time of global reorganisation of the system: it corresponds to the overturn time, and to the time it takes for a continent to move around the sphere (assuming a velocity of 3 cm y^{-1}). The cases with the longer periods are characterized by longer-wavelength flows. Indeed, increasing the yield stress (van Heck and Tackley, 2008) or the individual size of a continent (Rolf et al., 2012) results in longer wavelength of convection. This suggests that the longer periods in the supercontinent and stiff lithosphere cases could emphasise the fact that very large-scale plate boundary topologies could be stable over a very long time. However, additional calculations would need to be performed to investigate the origin of the long period evolution of the production rate of new seafloor.

6. Discussion

6.1. Limitations

Tectonic reconstructions and convection models presented here have limitations that must be acknowledged when making interpretations. As already explained, uncertainties in the reconstructions depend on the quantity and quality of available data, which generally decrease going further back in time. Another source of uncertainty comes from the limitations of plate tectonics theory, since deformation in continents and in some specific areas in ocean basins is diffuse. However, the reconstructions presented here do take some large-scale deformation of continents into account. Convection models are themselves limited in resolution and in the physics for which they solve. Indeed, the targeted 1km resolution suggested by static studies, is out of reach

(Alisic et al., 2012). As a consequence, the convective vigour is here lower than that of the Earth's mantle and the impact of the evolution of convective vigour because of decaying radioactive heat sources is not studied here. The material properties are much more complex on Earth, and the rheology employed is simplified compared to what is expected for mantle rocks (Bercovici and Ricard, 2012). These limitations arise because of computational resources and experimental/theoretical gaps. The most important symptoms of these limitations in the present models are the difficulty in obtaining continents that break up as efficiently as on Earth, and existence of symmetric subduction in oceanic regions (plates on both sides of the suture sink). Solving these issues is work in progress (Crameri et al., 2012). Current computational limitations forced us to be limited to 6 convection calculations; however, due to the rapidly expanding power of high performance computers it will be possible to explore this parameter space better in the near future.

6.2. Convergence of tectonic reconstructions and convection models

Both tectonic reconstructions and convection models show that the distribution of seafloor ages varies significantly over 200 My. Indeed, periods of tectonic quietness display area-age distributions that are rectangular-like with small production rates of new seafloor, while periods of generation of new plate boundaries feature area-age distributions that are skewed with the maximal production rate of new seafloor. Intermediate periods have more triangular-like distributions as the Earth has today.

The production rate of new seafloor varies by a factor of 2 in both tectonic reconstructions and convection models, and fluctuates over various timescales, including a 200 My timescale that corresponds to the maximum age of the seafloor. Such variations corroborate the hypothesis that the present-day area-age distribution results from strongly time-dependent production of new seafloor (Demicco, 2004; Becker et al., 2009; Seton et al., 2009). The rms surface velocity varies significantly in both reconstructions (Conrad and Lithgow-Bertelloni, 2007; Seton et al., 2009) and models, correlating with production of new seafloor. However, reconstructions and convection models suggest that changes in ridge length are as important as changes in rms surface velocity regarding fluctuation of seafloor production. The reconstructions in Figure 3 and the convection sequence in Figure 5 display significant ridge length changes. For example, the development of the ridge systems in the Tethys and Atlantic Oceans in the Early Cretaceous (Figure 3) corresponds to increases in ridge length and spreading rate by 20% and 40% respectively, concomitantly with an 30% increase in crustal production (Seton et al., 2009). In the convection sequence, direct measurements on the 664 Ma and 603 Ma synthetic maps lead to a ridge length increase by 20%±5% in 61 My caused by the development of a new ridge system (Figure 5).

This convergence holds with the different yield stresses (producing plate-like behavior) and with a limited amount of core heating. Tectonic reconstructions and convection models suggest that both time-dependence and the geometry of the flow/continental boundaries play an important role in the consumption of young seafloor.

6.3. Predictions of convection models over longer timescales

The convection models provide the long timescale perspective. Our calculations show that variability of seafloor spreading over timescales longer than 200 My is significant. However, no other end-member distributions than rectangular-like, triangular-like and skewed are observed. The production rate of new seafloor evolves also over 600-900 My, which may correspond to the time needed to reorganise the convective flow on a global scale. Long periods suggest that some oceanic domains could persist for almost 1 Gy. The Pacific domain, being a remnant of Panthalassa, could represent a potential example.

Convection models question the existence of sudden peaks of production of new seafloor reaching 2.5 times the average value. Such events, displaying very intense generation of new ridges and subduction zones, and disruption of the plate organisation, happen over a 600-900 My period. They are not necessarily correlated with peaks of plate velocity. However, these peaks do not exist if the lithospheric strength is higher while still obtaining smoothly-evolving plate tectonics (i.e. avoiding the episodic tectonics regime). As a consequence, additional observations are needed to evaluate if such dynamics is relevant to the Earth. Sea-level reconstruction in deep time, for instance, could help to qualify the relevant behaviour for the lithosphere to be used in convection models.

7. Conclusions

Although they are independent modelling approaches, both tectonic reconstructions and convection models with plate-like behaviour and continental lithosphere converge to support that seafloor spreading fluctuates significantly over 200 My. Indeed, the shape of the area-age distribution is time-dependent and changes from rectangular-like in periods of tectonic quietness, to skewed in periods of generation of new plate boundaries. The triangular-like distribution of the present-day Earth corresponds to an intermediate state. In the past 200 My, aggregation of Pangaea led to a quiet period and dispersal phases involved subsequent skewed distributions. The convection models show that seafloor spreading dynamics itself, without significant continental drift, can lead to such time-dependence. Therefore, both kinematic reconstructions and convection models converge to show that the area-age distribution of the seafloor does not remain triangular. Over a period of 200 My, the production rate of new seafloor varies by a factor of 2 in both tectonic reconstructions and convection models. Both reconstructions and convection models suggest that changes in ridge length are as important as changes in spreading rates. Time-dependence over longer timescales (600-900 My and eventually >1 Gy) is suggested by convection models. As a consequence, some oceanic domains could persist for periods as long as Wilson cycles and eventually longer. Sudden and extreme peaks of production of new seafloor may exist sparsely over time, occurring at most once every billion years. However, observations are needed to constrain the strength of the lithosphere in convection models to confirm the existence of such events on Earth.

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Figures

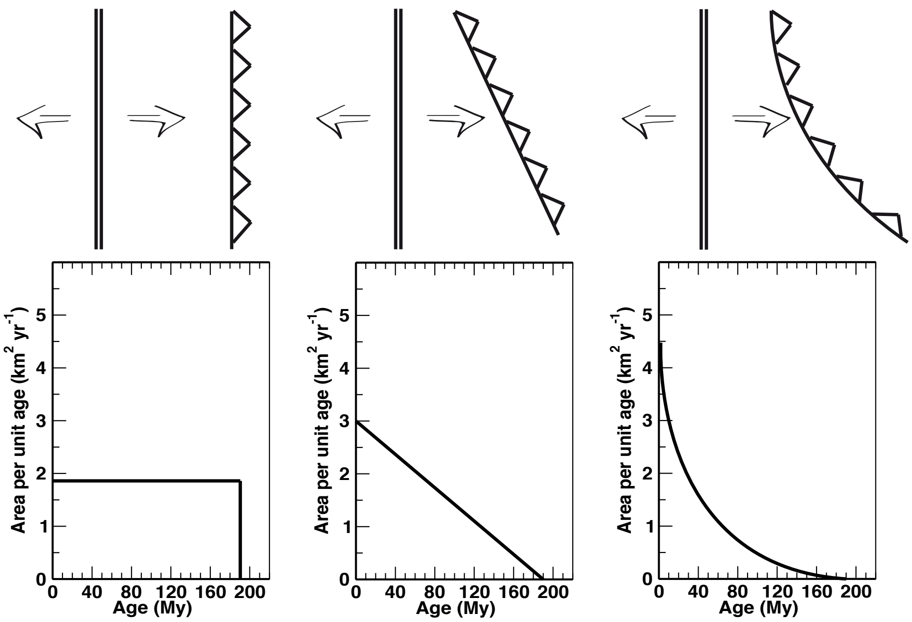

Figure 1: The shape of the area-age distribution depends on the geometry of plate boundaries.

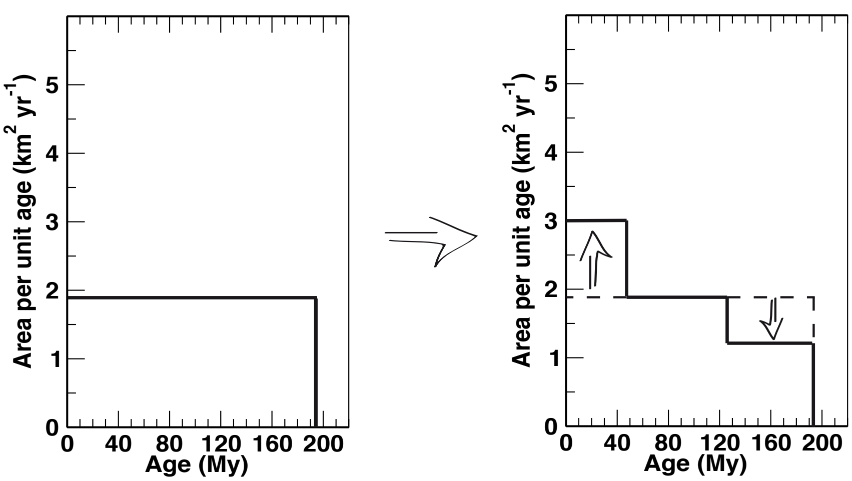

Figure 2: The time dependence of the production of new seafloor implies changes of shape of the area-age distribution.

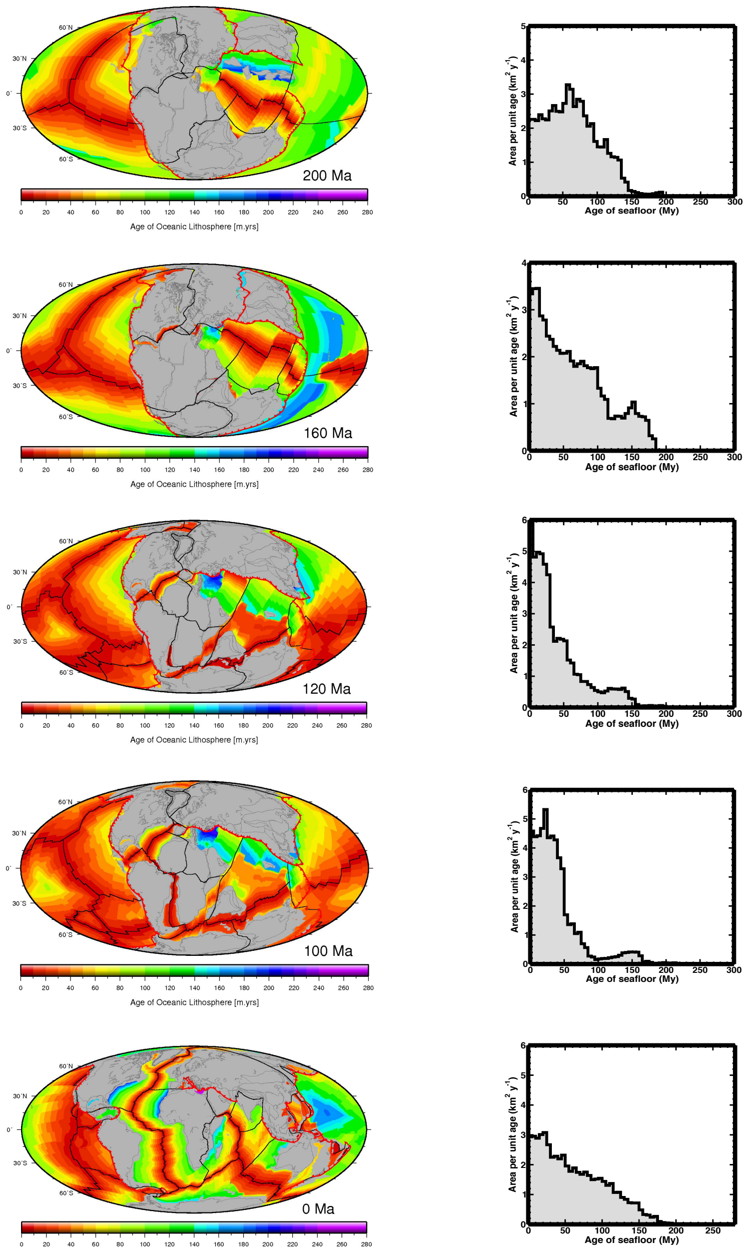

Figure 3: Maps of reconstructed distribution of seafloor ages and associated area-age distributions in the past 200 My (Seton et al., 2012).

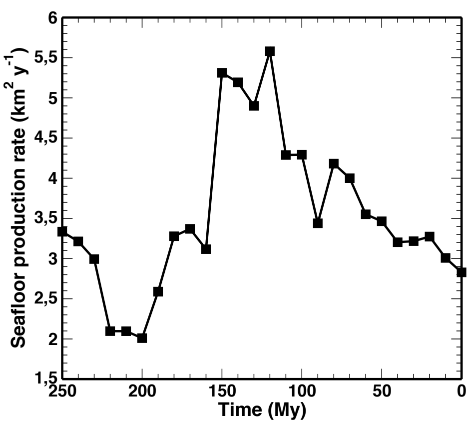

Figure 4: Reconstructed evolution of the rate of production of new seafloor derived from the plate tectonic reconstructions of Seton et al. (2012).

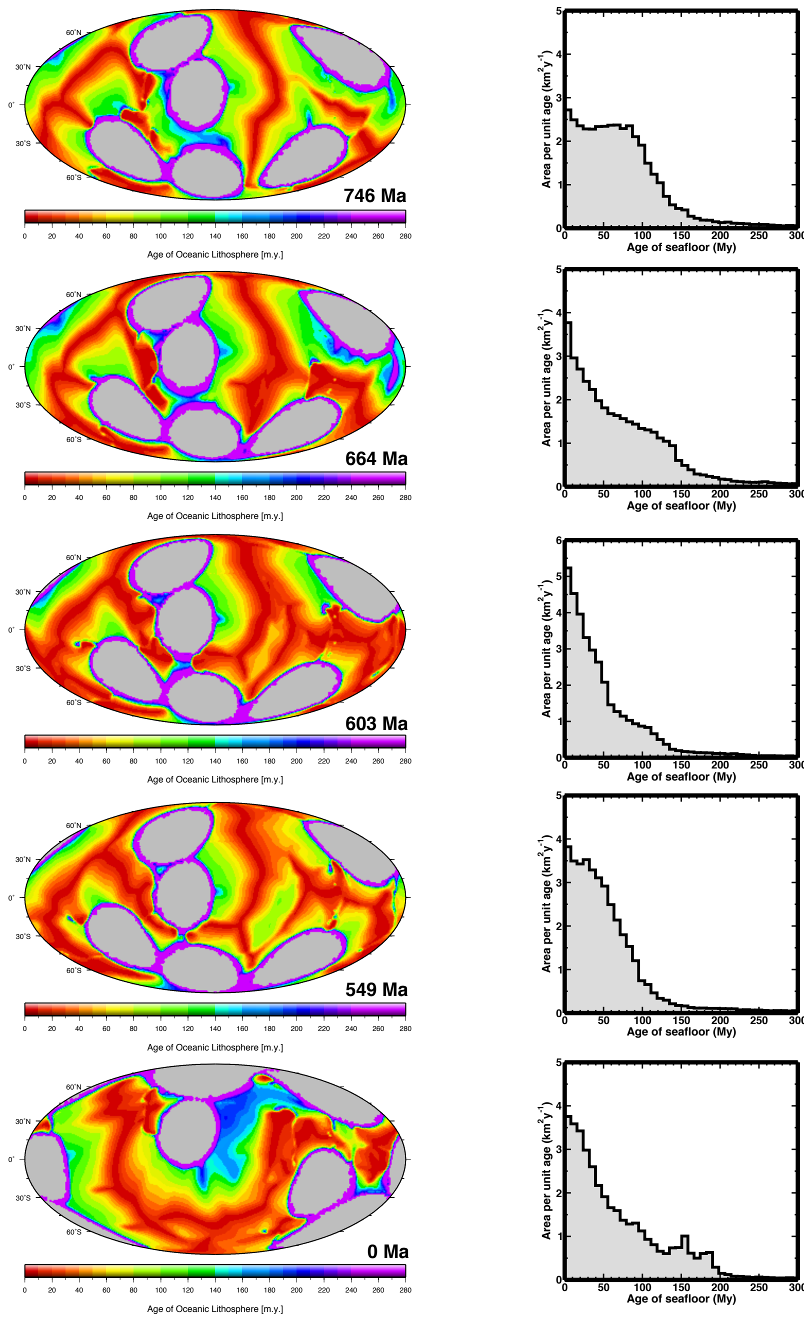

Figure 5: Synthetic maps of seafloor ages and associated area-age distributions in the mantle convection model with 6 continental rafts and 14% of core heating. The gray area represents the continental area. The selected results present 200My of evolution in the first four raws and the situation 549My after that 200My evolution.

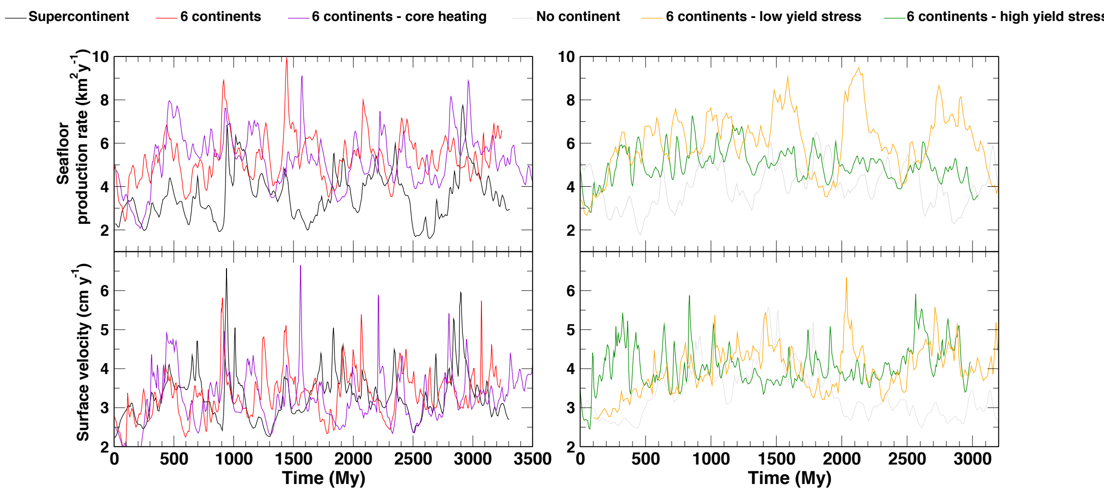

Figure 6: Computed evolution of the rate of production of new seafloor and RMS surface velocity in convection models. The solutions are for an intermediate yield stress value of 10^4, except for the low (5000) and high yield stress solutions ($2\ 10^4$). Core heating corresponds to 14% of the whole heat budget.

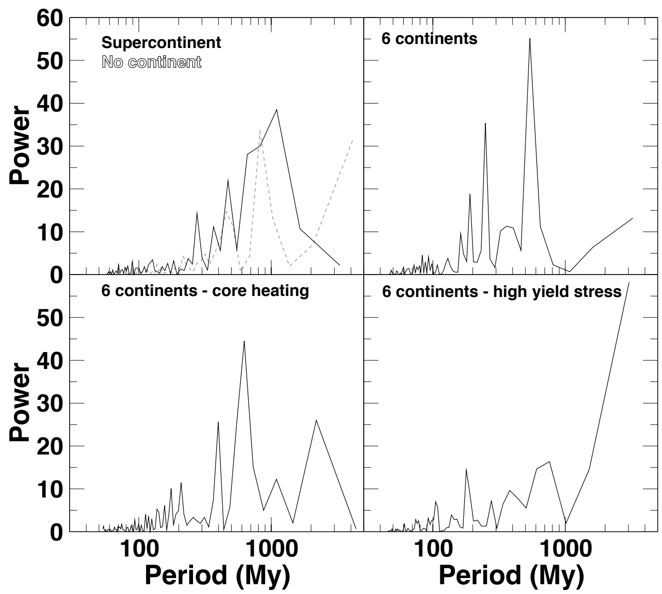

Figure 7: Periodograms of the production rate of new seafloor in the mantle convection models obtained by Fourier transform of the time-series. Periods with large power dominate the spectral content of the time-series and can be interpreted as the characteristic timescales of the system.